

Isolated leptons from heavy flavor decays: Theory and data

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Abstract

Events with isolated leptons play a prominent role in signatures of new physics phenomena at high energy collider physics facilities. In earlier publications, we examine the standard model contribution to isolated lepton production from bottom and charm mesons and baryons through their semileptonic decays $b, c \rightarrow l + X$, showing that this source can overwhelm the effects of other standard model processes in some kinematic domains. In this paper, we show that we obtain good agreement with recent Tevatron collider data, both validating our simulations and showing that we underestimate the magnitude of the heavy-flavor contribution to the isolated lepton yields. We also show that the isolation requirement acts as a narrow bandpass filter on the momentum of the isolated lepton, and we illustrate the effect of this filter on the background to Higgs boson observation in the dilepton mode. We introduce and justify a new rule of thumb: isolated electrons and muons from heavy-flavor decay are produced with roughly the same distributions as b and c quarks, but with 1/200 times the rates of b and c production, respectively.

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I. INTRODUCTION

Isolated leptons along with missing transverse energy \cancel{E}_T are typical signatures for new physics processes at collider energies. A much-anticipated example of charged dilepton production is Higgs boson decay, $H \rightarrow W^+W^-$ followed by purely leptonic decays of the W intermediate vector bosons. Charged trilepton production may arise from the associated production of a chargino $\tilde{\chi}_1^\pm$ and a neutralino $\tilde{\chi}_2^0$ in supersymmetric (SUSY) models, followed by the leptonic decays of the chargino and neutralino.

There are many standard model (SM) sources of isolated leptons. The nature and magnitude of contributions from semileptonic decays of heavy flavors (bottom and charm quarks) are emphasized in two papers [1, 2]. The role of heavy flavor backgrounds in $H \rightarrow W^+W^- \rightarrow l^+l^- + \cancel{E}_T$ at Fermilab Tevatron and CERN Large Hadron Collider (LHC) energies is presented in Ref. [1]. We simulate the contributions from processes with b and c quarks in the final state, including $b\bar{b}X$, $c\bar{c}X$, Wc , Wb , $Wb\bar{b}$. In Ref. [2], we study the signal and backgrounds for $\tilde{\chi}_1^\pm\tilde{\chi}_2^0 \rightarrow l^+l^-l^\pm + \cancel{E}_T$. We include heavy-flavor contributions to the backgrounds from bZ/γ^* , $b\bar{b}Z/\gamma^*$, cZ/γ^* , $c\bar{c}Z/\gamma^*$, $b\bar{b}W$, and $c\bar{c}W$. We learn that isolation cuts do not generally remove leptons from heavy-flavor sources as backgrounds to multilepton searches. A sequence of complex physics cuts is needed, conditioned by the new physics one is searching for. Moreover, the heavy-flavor backgrounds cannot be easily extrapolated from more general samples. The interplay between isolation and various physics cuts tends to emphasize corners of phase space rather than the bulk characteristics. While the heavy-flavor backgrounds can be overwhelming, we propose specific new cuts that can help in dealing with them, and we suggest methods for *in situ* verification of the background estimates.

Our finding that the dominant backgrounds to low-momentum dilepton and trilepton signatures come from real b and c decays may be met with some skepticism. Since our publications, important Collider Detector at Fermilab (CDF) data [3] have appeared that allow us to make a quantitative comparison at Tevatron collider energies. We report the results of our comparison in this paper. Specifically, these data allow us to verify how well we model isolation of leptons for events classified as originating from the “Drell-Yan” processes, in which virtual photons γ^* and intermediate vector bosons W and Z are produced and decay into leptons. In addition, since we predict the absolute rate of heavy-flavor production and

the Drell-Yan processes, we can check whether the data agree with our prediction of the rates of isolated leptons from these sources.

In Sec. II, we present our detailed comparison with the CDF data, using the same control regions defined in their study, and using the same detector simulations and event generation methods of our previous papers [1, 2]. We obtain good agreement with the CDF data, both validating our simulations and showing that our estimates of the magnitude of the heavy-flavor contribution are conservative.

The added confidence in our understanding of the backgrounds from heavy-flavor sources motivates another look at one aspect of our study of $H \rightarrow W^+W^- \rightarrow l^+l^- + \cancel{E}_T$. Our results show a sharp fall of the contribution from heavy-flavor decays at large values of the dilepton transverse mass distribution. This falloff is too steep to reflect only the drop with transverse momentum of the cross section for heavy-flavor production. In Sec. III, we explain how isolation serves as a narrow bandpass filter on the momentum of the leptons, thus explaining the steep decrease at high mass.

A discussion of the implications of our results is found in Sec. IV. We utilize the effect of the bandpass filter on b and c decays as a way to develop a simple rule-of-thumb that 1/200 of every produced bottom or charm quark is seen as an isolated muon, and another 1/200 is seen as an isolated electron, each with roughly the momentum of the heavy quark. We end this introduction with a general discussion of isolation and a summary of its effects.

Given a lepton track and a cone of size ΔR in rapidity and azimuthal angle space, the lepton is said to be *isolated* if the sum of the transverse energy of all other particles within the cone is less than a predetermined value (either a constant or a value that scales with the transverse momentum of the lepton). Our simulations based on the known semileptonic decays of bottom and charm hadrons show that leptons which satisfy isolation take a substantial fraction of the momentum of the parent heavy hadron. Moreover, isolation leaves $\sim 7.5 \times 10^{-3}$ muons per parent b quark. The potential magnitude of the background from heavy-flavor decays may be appreciated from the fact that the inclusive $b\bar{b}$ cross section at LHC energies is about 5×10^8 pb. A suppression of $\sim 10^{-5}$ from isolation of two leptons still leaves a formidable rate of isolated dileptons. For the isolated leptons, our simulations show that roughly 1/2 of the events satisfy isolation because the remnant is just outside whatever cone is used for the tracking and energy cuts, and another 1/2 pass because the lepton took nearly all the energy, meaning there is nothing left to reject upon. The latter

events are not candidates to reject with impact parameter cuts since they tend to point to the primary vertex. Although the decay leptons are “relatively” soft, we find that their associated backgrounds extend well into the region of new physics with relatively large mass scales, such as a Higgs boson with mass ~ 160 GeV.

II. COMPARISON TO CDF

In their analysis of isolated leptons from b decay [3, 4], CDF defines several control regions in order to disentangle the effects of different backgrounds. In Fig. 1, we reproduce Fig. 5 of their paper [3] displaying the various regions. In order, control region Z is the Z -boson resonance, and corresponds to an opposite-sign dimuon invariant mass acceptance of $76 < M_{\mu^+\mu^-} < 106$ GeV. Region A is a low missing transverse energy region, with $\cancel{E}_T < 10$ GeV and $M_{\mu^+\mu^-} > 10.5$ GeV. The CDF region S is designed as a signal region for their trilepton study (but examines dimuons here) with $\cancel{E}_T > 15$ GeV, ≤ 1 jet, $M_{\mu^+\mu^-} > 15$ GeV, and excludes region Z. Regions B, C, and D complement region S: region B is a subset of region Z, with $\cancel{E}_T > 15$ GeV; region C is a subset of region A with $M_{\mu^+\mu^-} > 15$ GeV and excludes the overlap with region Z; and region D is the same as region S, but requires at least 2 jets.

Our goal is to compare directly with the CDF measurement of isolated leptons from b decay [3, 4] in each of the control regions defined above using exactly the same detector simulations and methods as our previous papers [1, 2]. We concentrate on the contributions from $b\bar{b}$ pair production, with the semileptonic decay $b \rightarrow \mu + X$, and the Drell-Yan process $p\bar{p} \rightarrow \gamma^*/Z + X$. We also consider the contributions from W bosons plus heavy flavors (Wc , Wb , $Wc + \text{jet}$, $Wb + \text{jet}$, $Wb\bar{b}$, and $Wc\bar{c}$), though they contribute significantly only to region S. We do not include muons from light-quark jets, such as K or π decays, which are usually classified as “fakes.” We also do not predict the rate of muons from $c\bar{c}$, as this was not separately identified by CDF.

We generate events with a customized version of MadEvent 3.0 [5] and run them through the PYTHIA 6.327 [6] showering Monte Carlo. Both programs use the CTEQ6L1 parton distribution functions [7] evaluated via an efficient evolution code [8]. The showered events are fed through a version of the PGS 3.2 [9] fast detector simulation, modified to match CDF geometries, efficiencies, and detailed reconstruction procedures [10]. At the level of individual reconstructed leptons and jets we reproduce CDF full detector simulations and

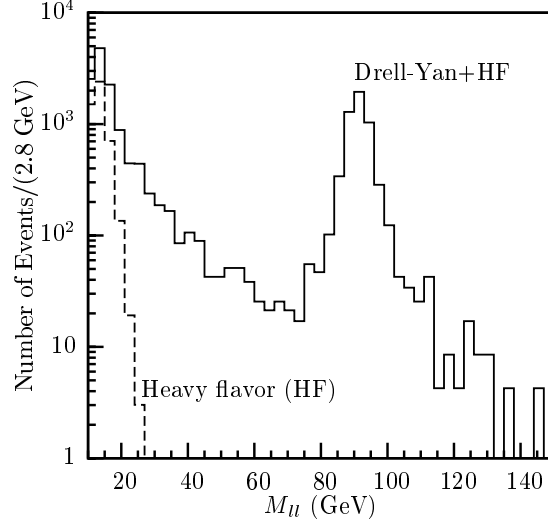


FIG. 2: Dimuon invariant mass distribution from Drell-Yan and heavy-flavor production in region A.

production in control regions A and C — the regions with the most statistical significance.

TABLE I: Comparison between the number of the Drell-Yan (DY) and $b\bar{b}$ events observed by CDF (from Table III of Ref. [3]) in each control region, and our predictions. Dashes indicate no events are expected or observed. (*) We could not obtain enough statistics in Control D to compare. ([†]) Includes 10 ± 3 events from $W + \text{heavy flavors}$ (mostly Wc).

| Region | CDF | | Our study | |
|-----------|------------------|-----------------|------------------|---------------------|
| | DY | $b\bar{b}$ | DY | $b\bar{b}$ |
| Control Z | 6419 ± 709 | — | 6419 ± 752 | — |
| Control A | 14820 ± 2242 | 9344 ± 1621 | 14222 ± 1615 | 5118 ± 584 |
| Control B | 217 ± 25 | — | 58.9 ± 24.9 | — |
| Control C | 5770 ± 1043 | 2238 ± 384 | 4898 ± 584 | 924 ± 117 |
| Control D | 7.8 ± 1.5 | 9 ± 4 | 9.8 ± 9.9 | —* |
| Control S | 169 ± 30 | 90 ± 20 | 226 ± 53.2 | $26 \pm 10^\dagger$ |

Once we have normalized to the observed luminosity, we find that our predictions systematically *underestimate* the number of isolated leptons from b decays in the overlapping control regions (A and C) by nearly a factor of two. This result suggests that our analysis has been conservative in estimating this generally ignored source of contamination. Part

of the observed difference may be due to the small K -factor of 1.4 we use to estimate the absolute normalization. However, even a K -factor of 2 would leave a systematic underestimate of 1.4. The remainder could be due to contamination from $c\bar{c}$ decays that produce isolated muons on one side of the event, and resemble b 's on the other side. Regardless, the background is not only a large fraction of the entire data set, but it is more significant than the estimations of Refs. [1, 2].

In our main analysis, we do not consider regions D and S of the CDF study significant for two reasons. First, the statistics are too small to make a definitive statement. Second, the choice of regions is sensitive to the reconstruction of missing transverse energy \cancel{E}_T , which is difficult to model at the level of 10–15 GeV. One concern may be that events have “slipped” from the low \cancel{E}_T regions to the high ones. If this were due to a systematic shift in our reconstruction it should also appear in the Drell-Yan sample. We see a hint of this in our Drell-Yan estimate for region S. However, we see the opposite effect in isolated leptons from heavy-flavor decays, where our prediction of 16 events from $b\bar{b}$ and 10 events from W + heavy flavors, underestimates the measured CDF region by a factor of 3.5.² The underestimate of isolated leptons from heavy-flavor decays in region S is consistent with our reduced estimate of Drell-Yan in region B.

Given that region Z overlaps both regions C and S, a comparison that should reduce the sensitivity to \cancel{E}_T would be between the sums of these regions. In that case, our Drell-Yan result (C+S) of 5124 ± 586 events does agree a bit better with the CDF observation of 5939 ± 1043 , but in both cases is within 1σ . If we consider isolated leptons from heavy-flavor decays, we find regions (C+S) have 950 ± 120 events, which is still approximately a factor of two smaller than the combined CDF regions of 2328 ± 385 . Hence, it appears unlikely that misestimations of \cancel{E}_T or W + heavy flavor decays, are responsible for our systematic underestimate of the heavy-flavor background.

Figure 2 demonstrates that the bulk of the CDF dimuon sample from heavy flavors is composed of muons with transverse momentum p_T less than 10 GeV. One limitation of our study is that our original detector simulation was constructed and tuned for leptons with $p_T > 10$ –20 GeV. It is somewhat surprising we are able to model the detector response as well

² Using the lower estimate of 70 events from the CDF measurement and our upper estimate of 36 events leads to the same factor of 2 under-prediction observed in other regions.

as we do. Perhaps the Z region, where we trust our detector simulation, is not representative enough of the low dilepton invariant-mass region. To this end, we also consider in Table II normalizing our $b\bar{b}$ contribution in each region independently. We do this by extracting the K -factor necessary to exactly scale our Drell-Yan calculation to the measured Drell-Yan rate, and applying that to our prediction of the $b\bar{b}$ contamination. Under this method, our predicted background from $b\bar{b}$ increases by less than one standard deviation, and it is still about a factor of 2 smaller than CDF data.

TABLE II: Comparison between the number of $b\bar{b}$ events observed in CDF control regions, and our predictions, where each region is normalized separately by the ratio of the CDF measurement of Drell-Yan production in that region divided by our prediction. ([†]) Includes 8 ± 3 events from W + heavy flavors (mostly Wc).

| Region | CDF | Our study |
|-----------|-----------------|----------------------|
| Control A | 9344 ± 1621 | 5333 ± 833 |
| Control C | 2238 ± 384 | 1089 ± 213 |
| Control S | 90 ± 20 | $20 \pm 8^{\dagger}$ |

We conclude this section with the statement that our estimate of the contamination to isolated lepton sample from heavy-flavor decays appears conservative.

III. LEPTON ISOLATION ACTS AS A MOMENTUM FILTER

Having experimental verification that isolated leptons from heavy flavor decays play an important role, we clarify one aspect that experimental reconstruction has on the spectrum of these leptons. In Sec. II of Ref. [2], we explain in detail how leptons from b and c decays pass isolation cuts. Briefly, the probability to produce a lepton above some threshold, e.g., $p_{T\mu} > 10$ GeV is convolved with the probability of missing the rest of the b or c decay remnant. For completeness, we reproduce the shape of this efficiency using an ATLAS-like detector simulation for muons as a function of the p_{Tb} of the quark in Fig. 3.

When the acceptance function is folded with a typical b transverse momentum spectrum — whether from $b\bar{b}$ production, or any other spectrum that falls with p_T — the peak of the resulting cross section of isolated muons comes from b 's whose p_T is just above the muon

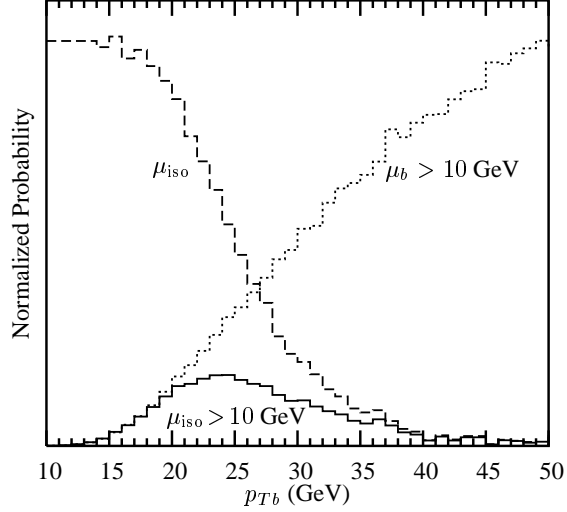


FIG. 3: Normalized probability for a b quark to produce an isolated muon with $p_{T\mu} > 10$ GeV (solid) vs. the b transverse momentum [2]. This curve is a multiplicative combination of the probability of producing a muon with $p_{T\mu} > 10$ GeV (dotted) and the probability the muon will be isolated (dashed). The b production spectrum is not included.

p_T . This effect is clearly present in Fig. 4, where the peak for muons with $p_{T\mu} > 10$ GeV in $b\bar{b}$ production comes from 20 GeV b 's. Previously [2], we focused on the low-momentum end of this spectrum, noting that a significant fraction of isolated leptons arise from b 's just above threshold for production. Hence, to properly model this background, b and c must be modeled all the way down to threshold.

In this section, we focus on the upper end of the isolated lepton spectrum as a function of b (or c) transverse momentum. The long tail of acceptance in Fig. 3 is suppressed by the sharply falling b transverse momentum spectrum. The net result is that the isolation acts as a *narrow bandpass filter on momentum*. This observation has a critical importance for higher-scale physics, such as Higgs boson production.

In the dilepton analysis of a Higgs boson decaying to W^+W^- to dileptons we observe that the transverse-mass M_T spectrum due to $b\bar{b}/c\bar{c}$ and W +heavy flavors drops sharply at large M_T . In Fig. 5(a) the background from heavy flavors falls through the middle of Higgs boson signals for masses in the range 140–200 GeV. Raising the p_T threshold of the *second-highest* p_T lepton from 10 GeV to 20 GeV pushes this leading edge to lower transverse mass, Fig. 5(b), thereby recovering our ability to extract a Higgs signal in the dilepton channel despite

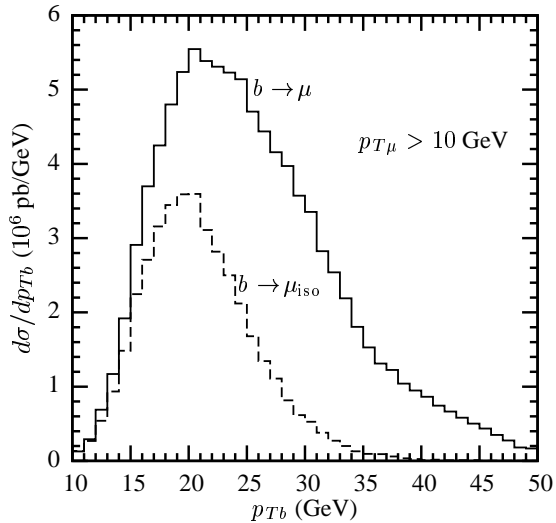


FIG. 4: Cross section for production of a muon of $P_{T\mu} > 10$ GeV from $b\bar{b}$ production and decay (solid), or an isolated muon (dashed).

the heavy-flavor background.

Considering lepton isolation criteria as a *narrow bandpass filter*, we see that the sharp high- M_T edge is due to the cutoff of large-momentum b 's by this filtering mechanism. Hence, even though we are modeling the tail of a steeply falling spectrum, the filtering effect of lepton isolation acts to safely suppress the region where we expect our M_T shapes to be less-well defined. The net result of this filter is to provide a more robust determination of the shape of the background from isolated leptons.

IV. DISCUSSION

In this paper we predict the rate of isolated muons from b decay in order to compare directly with data from the CDF Collaboration. The central conclusion to draw is that isolated leptons from b decays are a large fraction of the low transverse momentum lepton sample. In the case of the CDF measurement we *under-predict* the measured rate of dimuons from b decay using the same codes and procedures we use to estimate the background to dilepton and trilepton signatures at the Tevatron and LHC [1, 2]. Hence, we are confident that these backgrounds will play an important role in the extraction of Higgs boson decays to WW , trilepton supersymmetry, and indeed all processes with any low transverse momentum electron or muon.

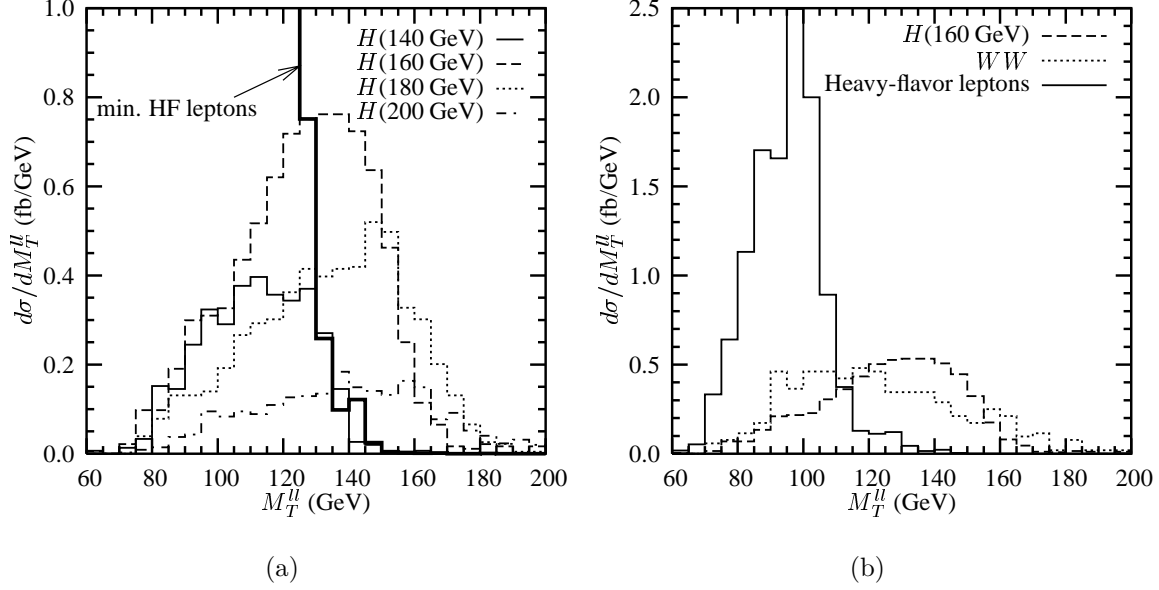


FIG. 5: (a) Opposite-sign dilepton transverse mass for various Higgs boson masses at $\sqrt{S} = 14$ TeV, and the additional heavy-flavor background (thick solid line), with default ATLAS cuts. (b) Opposite-sign dilepton transverse mass for a 160 GeV Higgs boson, the continuum WW background, and the additional heavy-flavor background after the p_{Tl_2} threshold of the *second*-highest transverse momentum lepton is raised from 10 GeV to 20 GeV [1].

Given the broad nature of our conclusions, and the significant computing resources required to model these backgrounds properly, we introduce a new “rule-of-thumb” to determine whether these leptons may be problematic in any given analysis:

- Replace 1/200 of every produced b or c quark with a muon, and 1/200 with an electron having the same momentum as the b or c .
- If the resulting background is more than 10% of the signal, it should be simulated more carefully, and eventually measured *in situ*.

This new rule-of-thumb works precisely because the lepton isolation criteria act as a bandpass filter selecting leptons from b or c quarks whose transverse momenta are only slightly above the momentum of the lepton. In general, this rule-of-thumb is valid for large transverse momentum leptons as well. Fortunately, the production rates for b and c quarks tend to fall rapidly (with the exception of b decays from top quarks, which peak near 50–60 GeV). Overall, we strongly recommend that all analyses involving leptons consider the background

from the decay of heavy-flavor hadrons, as many analyses are sensitive to regions of phase space in which this background is enhanced.

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